



Reduced Boil-Off System Sizing

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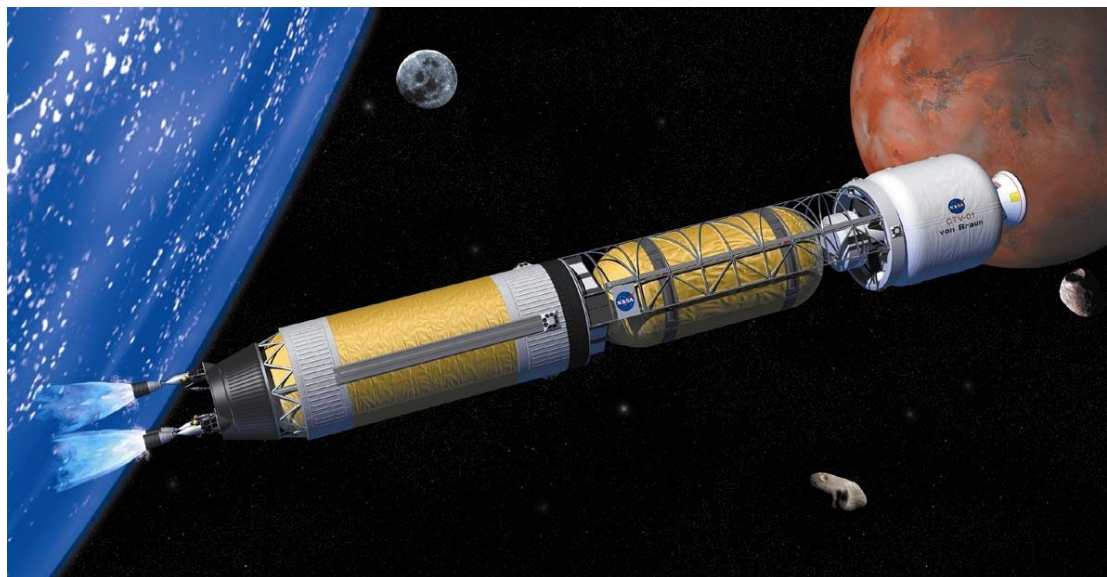
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Introduction

- NASA is developing capabilities to take exploration crews beyond Low Earth orbit (LEO)
 - Liquid hydrogen (LH₂) and liquid oxygen (LOX) propellants provide highest efficiencies
 - Increased exploration necessitates longer mission durations
 - Due to its low boiling point, LH₂ is difficult to store over long duration missions





Cryogenic Boil-Off Reduction Systems

- To increase mission duration capability, distributed cooling systems can be applied to intercept heat entering the propellant to achieve Reduced Boil-Off (RBO) or Zero Boil-Off (ZBO)
- RBO and ZBO can be achieved by utilizing a Broad Area Cooling (BAC) network of distributed tubing
 - For LH₂ RBO, a tube-on-shield approach is used, in which the BAC tubing is installed on a shield within the MLI
 - For LH₂ ZBO, a tube-on-tank approach is used with the BAC tubing installed directly on the tank surface
 - Due to the low efficiency and technical readiness of 20 K stage cryocoolers required for LH₂ ZBO, the tube-on-shield concept is the lowest mass approach

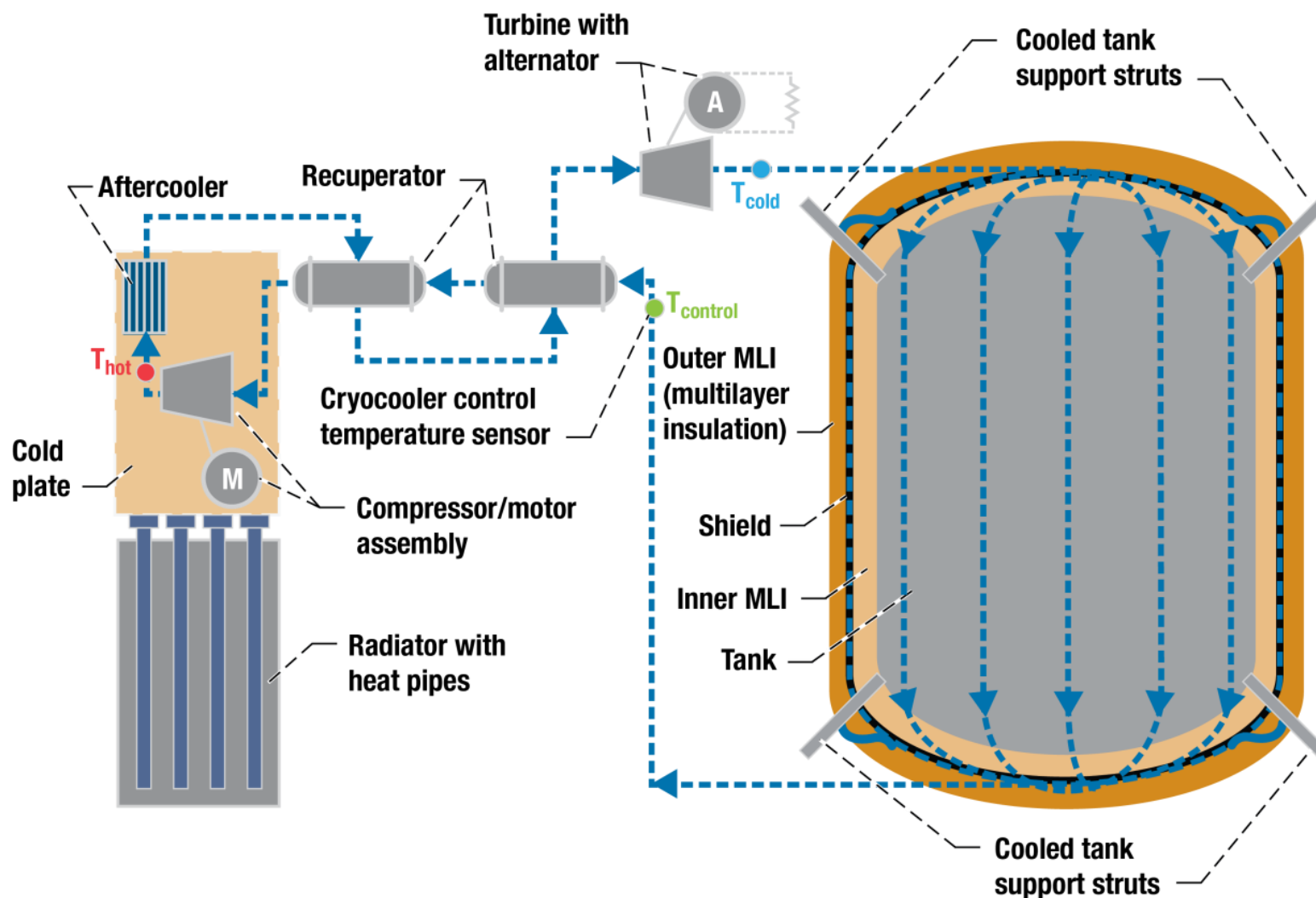
NASA GRC Reduced Boil-Off Efforts

- Cryogenic Boil-Off Reduction System Testing occurred in 2012-2013 at NASA GRC¹
 - A 90 K stage Reverse Turbo-Brayton Cycle (RTBC) cryocooler was used in combination with a BAC network installed on a shield within the tank's MLI layers
 - Two versions of MLI were tested beneath the BAC shield: traditional MLI, and self-supporting MLI (SSMLI)
 - Penetration elements were also cooled by the use of conductive cooling straps linked to the BAC tubing



1. Plachta, et al. "Cryogenic Boil-Off Reduction System Testing." AIAA/ASME/SAE/ASEE Joint Propulsion Conference; 50th; 28-30 Jul. 2014; Cleveland, OH.

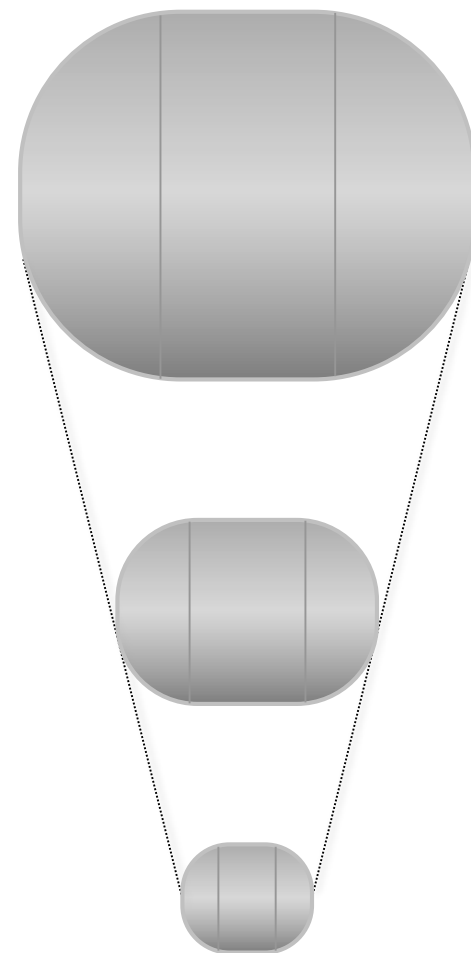
Cryogenic Boil-Off Reduction System Concept

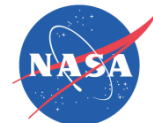




NASA Cryogenic Boil-Off Reduction System Scaling Analysis

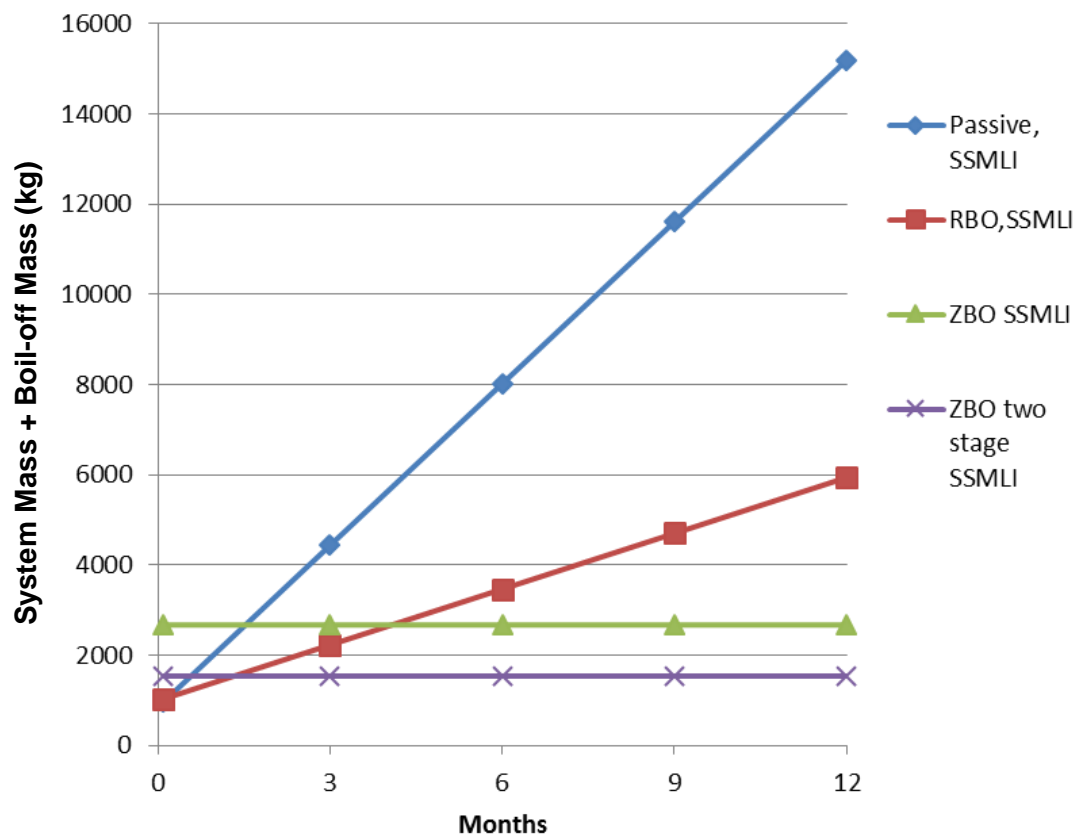
- In 2012, NASA performed an Active Thermal Control Scaling Study² to determine how current ZBO and RBO thermal control concepts scale up to large applications
- Focus was on scaling the Cryogenic Boil-Off Reduction System Concept for the 2012/2013 testing to future missions
- Preliminary results were reported, but not linked to most recent test results





Potential Mission Savings with RBO

- For a large 8.4m diameter LH2 tank, it was shown that active thermal control begins to have a positive impact on mission mass savings after a loiter period of several weeks, with significant savings after 6 months²

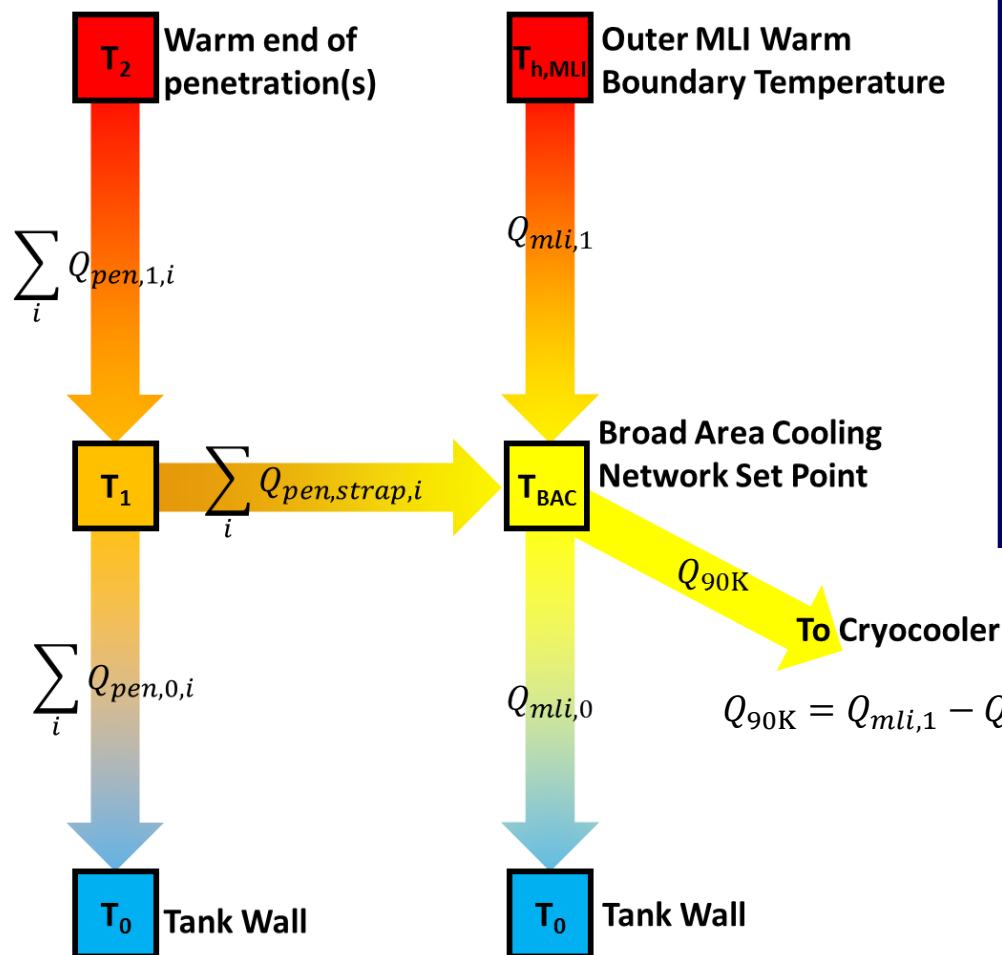




Sizing an RBO System for LH₂ Storage

- Problem: Present model iterates on RBO sizing, as part of a two stage cooling concept
 - No direct calculation of RBO stage was attempted
 - Data from RBO testing was used for validation
 - Broad Area Cooling shield data
 - Discrete cooling strap performance data
 - Conductive heat into the propellant tank liquid is intercepted at tank supports, piping and electrical penetrations
 - High conductivity straps from these tank penetrations are attached to BAC shield
- Solution enables mission designers to perform conceptual RBO design early in design process (prior to Mission Concept Review)
 - Requires ability to quickly size a system based on lowest number of mission-specific variables
 - A conductance-based model allows for rapid determination of heat leak and performance benefits without a detailed CAD geometry and thermal analysis
 - Sizing parameters for the RTBC cryocooler can be narrowed down to fractional pressure drop of the coolant loop and required heat lift
 - Heat leak entering tank can be used to directly size a 20K stage for ZBO

Modeling the 90K Stage



Heat enters the system primarily through the MLI and the penetrations, which include both structural and plumbing elements.

Heat leak entering the 90 K stage is a result of heat intercepted by the BAC shield within the MLI layers and heat entering the BAC tubing via cooling straps to the penetrations

$$Q_{90K} = Q_{mli,1} - Q_{mli,0} - Q_{stand-offs} + Q_{parasitic} + \sum_i Q_{pen,strap,i}$$

$$Q_{tank} = Q_{mli,0} + Q_{stand-offs} + \sum_i Q_{pen,0,i} + Q_{other}$$



Quantifying MLI Heat Leak

- The Lockheed equation 4.55^3 is well established as the baseline for calculating heat flux through an MLI blanket
- Scale factors, which adjust the Lockheed Equation for inefficiencies in the MLI such as seams and installation defects, are an input to model
- For MLI outside of BAC shield, Lockheed scale factor of 3.5 is assumed
 - CBRS I and II had Lockheed scale factors of 4 and 3 for outer MLI
 - LOX ZBO testing has Lockheed scale factor of 4, with 220 K shroud
 - MLSTC testing had Lockheed scale factor of 5.2 with 250 K shroud
- Due to the need to support the BAC shield as well as the MLI above it, self-supporting MLI (SSMLI) was selected for use between the shield and the tank
 - It is simpler to predict SSMLI heat flux using a layer-by-layer model due to its uniformity between layers
 - CBRS testing shows that, for SSMLI supporting a BAC shield, a scale factor of 3.0 should be applied to the heat flux
 - Test results for “passive” had scale factor of 2
 - Test results for “active” had scale factor of 5.5; Mylar emissivity is likely problem
 - Follow on MLI calorimeter work from 20-90K will better understand emissivity issue

Quantifying Strap Resistance

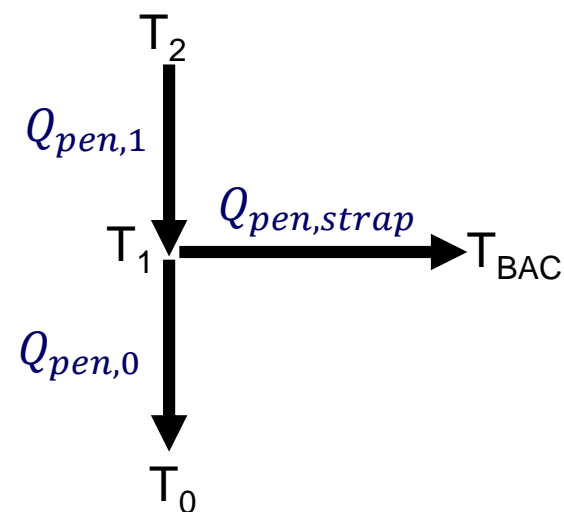
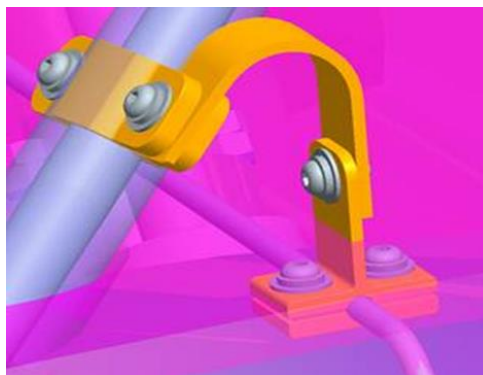
- A conductive strap can be used to intercept heat from a penetration element and direct it into the BAC system manifold
- Based on CBRs testing, a strap resistance of 10 K/W is recommended
 - Testing showed a strap resistance between 4.5 and 12.0 K/W, dominated by the contact resistance at the tank attachment points
 - With further bench testing and better controlled clamp attachment procedures, 5 K/W is assumed for each clamp to get an overall strap resistance of 10 K/W

$$Q_{pen,1} = \left(\frac{A}{L}\right)_{pen} * k_{pen} * (T_2 - T_1)$$

$$Q_{pen,0} = \left(\frac{A}{L}\right)_{pen} * k_{pen} * (T_1 - T_0)$$

$$Q_{strap,pen} = \frac{(T_1 - T_{BAC})}{R_{strap,pen}}$$

$$Q_{strap,pen} = Q_{pen,o} - Q_{pen,i}$$





Modeling Validation

- Results were compared to CBRs II test data results
- Recommended conductance values and scaling factors were used in place of actual test design

	Multi-Layer Insulation		Strut Supports (6 total)		Vent Line*		Fill/Drain Line		Totals**	
	Model Results	Test Data	Model Results	Test Data	Model Results	Test Data	Model Results	Test Data	Model Results	Test Data
Heat leak Entering Intercept (W)	4.44	4.26	1.10	0.96	2.03	0.33	1.66	1.52	9.23	7.06
Heat Leak Entering BAC System (W)	4.02	3.61	0.98	0.76	1.596	0.22	1.46	1.33	8.06	5.92
Heat Leak Entering Tank (W)	0.42	0.65	0.12	0.20	0.43	0.11	0.20	0.18	1.17	1.14

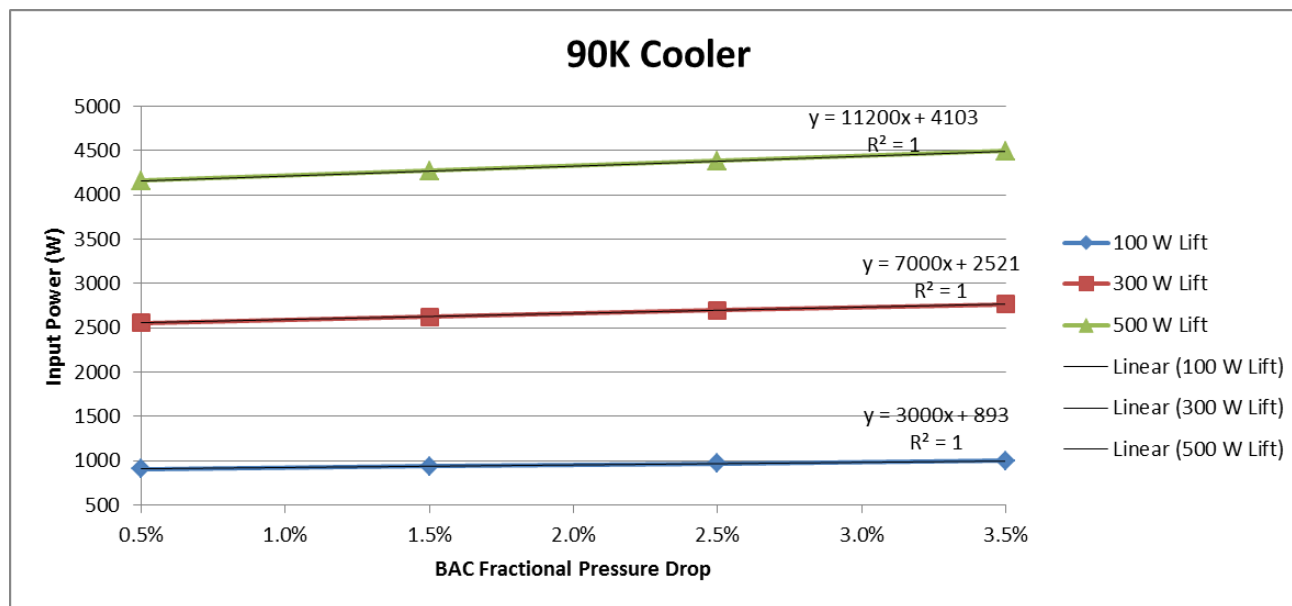
*The vent line was much colder than anticipated during test operation due to constant venting of cold GH2 vapor.

**Totals reflect only the components shown in the table, and do not include various heat sources such as instrumentation leads

Sizing a 90K RTBC Cryocooler Stage

- Following a contracted study with Creare, Inc, general sizing correlations were developed for an RTBC cryocooler system
 - The 90 K cryocooler stage can be sized based on fractional pressure drop and required heat lift
 - For general sizing estimates where fractional pressure drop is unknown, a value of 0.01 is recommended.

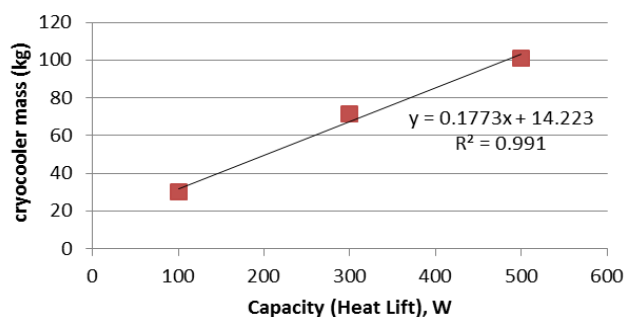
$$P_{input,DC} = 7.0667 \frac{\Delta p_{BAC}}{p_{inlet}} + 8.435 Q_{BAC} - 14.83$$



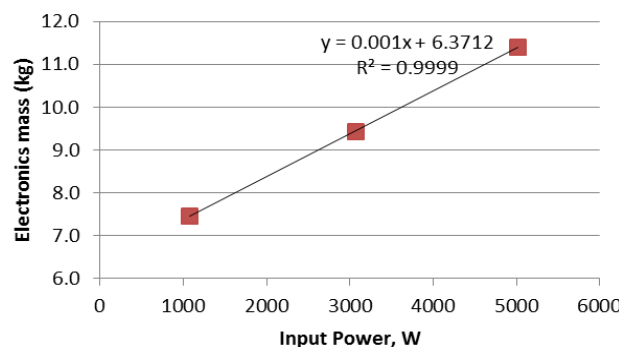
Sizing a 90K RTBC Cryocooler Stage

- Cryocooler system mass is the sum of the control electronics, cryocooler hardware, and structural support masses

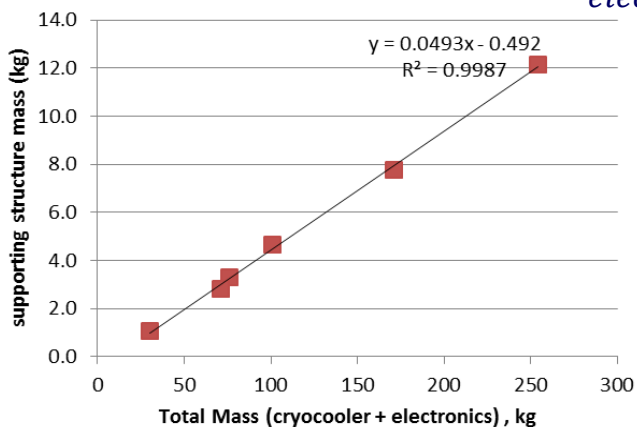
$$m_{total} = m_{electronics} + m_{cooler} + m_{support}$$



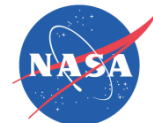
$$m_{cooler} = 0.1773Q_{BAC} + 14.223$$



$$m_{electronics} = 0.0011Q_{BAC} + 6.3577$$



$$m_{support} = 0.0493(m_{electronics} + m_{cooler}) - 0.492$$



Sample Results

- Results are shown for the CBRs test tank with recommended strap conductance and MLI scaling factors and a next-generation RTBC cryocooler. The fractional pressure drop is 0.01.

	No Active Cooling	Cooling With 90 K Stage
Heat Leak Entering Tank (W)	4.72	1.17
Boil-Off Rate (kg/day)	0.93	0.23
Heat Leak Entering Cooler (W)	0	8.06
Cooler Input Power (W)	0	123.8
Cryocooler Mass (kg)	0	22.8
Heat Rejection Required (W)	0	132.1



Conclusions

- Using CBRS test data, BAC and discrete cooling heat exchanger relationships were developed
- From those relationships, a conductance model was created for a mission designer to size a 90 K active thermal control stage
- For extended duration missions, the addition of a 90 K active thermal control stage may significantly reduce propellant tank boil-off losses
- Use of a 90 K stage greatly reduces the burden of heat lift--and associated power and mass--for the less efficient 20 K stage in the case of LH2 ZBO